Variation Sensitivity Study for an Aerospace Wing Spar Assembly

Variation Sensitivity Study for an Aerospace Wing Spar Assembly

Vincent MCKENNA[a,1], Yan JIN[a,2], Adrian MURPHY[a], Michael MORGAN[a], Rao FU[a], Caroline MCCLORY[a], Colm HIGGINS[a], Rory COLLINS and Xuda QIN[b]
[a] *Queen's University Belfast, Northern Ireland*
[b] *Tianjin University, China*

Abstract. Despite manufacturing sub-components to a high precision, large overconstrained assemblies are often impossible to assemble to tolerance limits when variations are present. This necessitates expensive and time consuming variation management processes at assembly, such as shimming. Existing research has not established a methodology to model the variation propagation mechanisms that results in this assembly variation. This paper presents such a methodology, which has the ability to quantify the assembly variation of overconstrained assemblies at the planning stage, providing useful data for determining the most appropriate combination of fabrication and assembly processes to use for a given case. The methodology is validated using an aerospace wing spar assembly, and a sensitivity study completed to rank the key variation drivers in the overconstrained assembly.

Keywords. Variation propagation, overconstrained assemblies, sensitivity study.

1. Introduction

The management of accumulated variation in overconstrained assemblies, which are common in the aerospace industry, is a challenging task for production planners. This is because the achievement of each assembly Key Characteristic [1] (KC) is not independent, therefore improving one KC can degrade another KC. Despite designers assigning tight tolerance requirements to sub-component manufacture, variation propagates and accumulates during manufacture and assembly, often making it impossible to achieve all assembly KCs within tolerance simultaneously. As a result, additional variation management processes such as shimming and fettling are required at the assembly stage, which are expensive and time consuming [2].

In order to quantify the cost implications of managing this excess variation at the planning stage, the variation must be characterised, and its magnitude estimated. However, the variation propagation mechanism for overconstrained assemblies is not currently well understood. Assembly variation modelling has been the subject of a large amount of research [3], which has established methods for modelling connective assemblies [4][5], and has facilitated the analysis of assemblies where parts are assembled through part-to-part mating surfaces [6][7][8]. To date, most assembly variation models have focused on the connective assembly relationships between parts. Overconstrained assemblies, however, present a unique challenge, as part relationships

[1] Corresponding Author. vmckenna02@qub.ac.uk. [2] Corresponding Author. y.jin@qub.ac.uk

can be spatial instead of connective. This means that the final variation at assembly is not simply equal to sub-component fabrication tolerances, as assembly variation is also affected by many other variation sources, such as fixture variation, fit-up errors and the alignment and orientation of parts in relation to each other in the assembly fixture. A method dealing with these potential variation sources has not been fully established in current variation models for overconstrained assemblies, creating a barrier to understanding the key variation drivers. This paper therefore presents a methodology to analyse and model variation propagation in overconstrained assemblies, and illustrates how key variation drivers can be identified using a sensitivity study.

2. Aerospace Case Study

To illustrate the challenge of overconstrained assemblies, an aerospace case study is presented. The case study consists of a section of an aircraft wing, consisting of a structural spar and four hinge brackets from an aircraft wing [2], as shown in Figure 1.

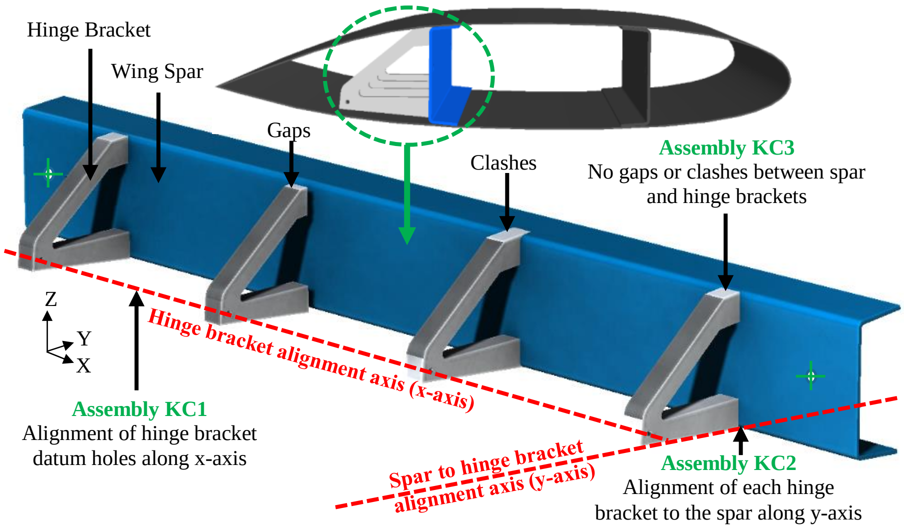

Figure 1. Spar and hinge bracket assembly.

The assembly is overconstrained, as the two mating feet per hinge bracket result in the spar being mounted at eight places along its span, which is five more than is required for location of the spar. There are three KCs which must be achieved in this assembly, highlighted in Figure 1. The first KC is the alignment of the four hinge brackets to each other along the hinge bracket datum hole x-axis. This is to ensure the correct operation of the aircraft control surfaces, which are mounted to the hinge brackets. The second KC that must be satisfied is the alignment of each of the four hinge brackets to the spar surface along the y-axis. This is to make certain that the assembly fits within the wing's airfoil profile. Finally, the third KC that must be achieved is the mating of the hinge bracket feet to the spar surface, without gaps or clashes occurring. This is to ensure the structural integrity of the overall assembly.

The case study is assembled using a fixture which spatially locates the spar and hinge bracket from each other. However, it has been found that all three KCs cannot be achieved simultaneously even when tight tolerances are assigned to the hinge bracket and spar fabrication processes. This is because the final assembly variation is a function of both variations induced at sub-component manufacture and variations induced during assembly itself. This results in expensive processes needing to be added to the production chain to manage the excess variation and bring the assembly within tolerance.

A study is therefore presented to analyse the major variation sources in the assembly, and subsequently derive the variation propagation mechanism. Determining where assembly variation occurs and at what magnitude is the novel deliverable of this research, and will aid production planners manage variation in overconstrained assemblies.

3. Variation Source Analysis and Variation Modelling

Variations can come from a wide range of sources [5] including but not limited to, individual component variations, variations due to small kinematic adjustments, fixture and assembly process variation and variations due to measurement errors are also possible [5]. Table 1 collates the variation sources considered in this paper. The typical magnitude of variation for machining processes [9], and the tolerance of CFRP processes [10] were used to define the likely manufacturing variation magnitude. Variation in fixture features and assembly positioning errors were estimated to be an order of magnitude smaller than manufacturing variations.

Table 1. Hinge bracket fabrication due to fabrication processes

Variation I.D.	Variation Source	Magnitude (mm)
Variation A – δA	Roughing and finishing machining cuts on aluminium	±0.1250
Variation B – δB	Drilling of datum hole in aluminium	±0.1900
Variation C – δC	Prepreg CFRP manufacturing process variations	±0.6000
Variation D – δD	Drilling of datum holes in CFRP	±0.2000
Variation E – δE	Fixture errors	±0.0100
Variation F – δF	Assembly positioning errors	±0.0100

The spar, hinge bracket and assembly feature were represented as coordinate frames, related to one another using homogeneous transformation matrices [11], and to the global datum, G. The part and feature naming convention used in this paper is as follows:

P_i *: the ith part* $\quad$ *i = 1, 2, 3, 4 …*
MFe_{ij} *: the jth mating feature of the ith part* $\quad$ *j = a, b, c, d …*
DFe_{ij} *: the jth datum feature of the ith part* $\quad$ *j = a, b, c, d …*
Fi_{ij} *: the jth fixture feature of the ith fixture* $\quad$ *j = a, b, c, d …*

The key part features and their variation sources are shown in Figure 2.

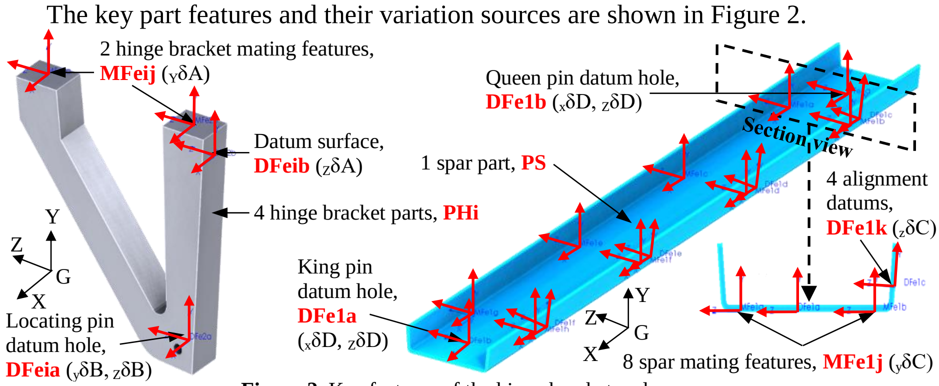

Figure 2. Key features of the hinge bracket and spar.

Different KC delivery chains will result in different magnitudes of assembly variation occurring at different locations in the assembly. Therefore, in order to model variation propagation in overconstrained assemblies, the order in which KCs will be achieved during assembly must be determined prior to modelling. The spar and hinge bracket case is described in Figure 3.

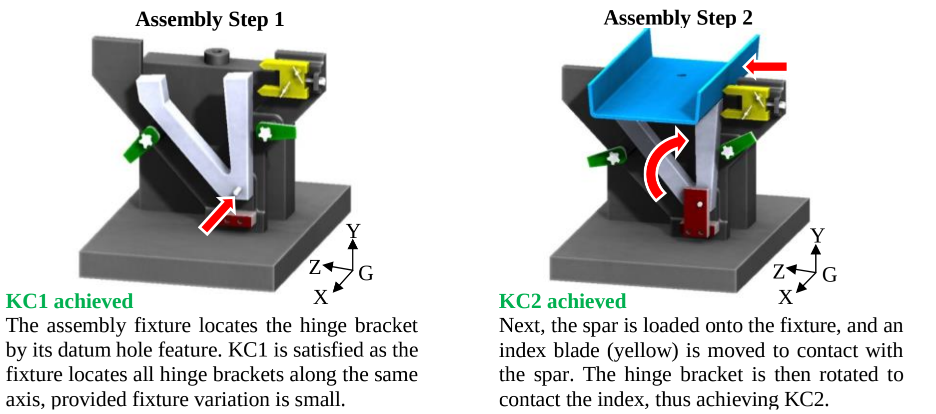

Figure 3. Assembly technique, including the achievement of KC1 and KC2.

The KC delivery chain is a consequence of the assembly technique. In assembly step 1, KC1 is achieved. At the next assembly step, KC2 is then achieved, without diminishing KC1. However, although KC1 and KC2 can be achieved simultaneously, it has been found that KC3 cannot be achieved as gaps or clashes between the spar and the hinge bracket feet are resulted, Variation at the KC3 mating interface is due to both manufacturing variation induced during spar or hinge bracket fabrication, and assembly variation due to fixture variation of the spar and hinge bracket locators. For example, variation changes when the hinge bracket is rotated to contact the index in order to satisfy KC2. The inability to achieve KC3 is shown in Figure 4, along with the fixture and assembly variation sources.

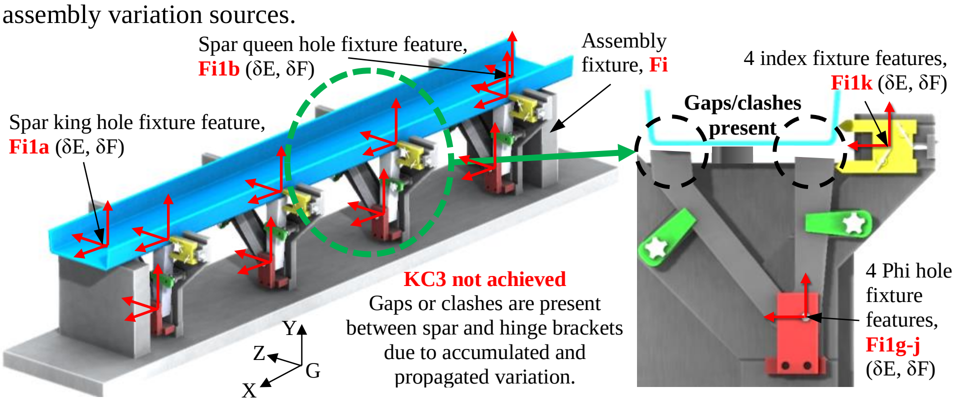

Figure 4. Assembly variation between spar and hinge bracket at KC3.

Whereas manufacturing variation can be readily measured during inspection, and controlled through tolerance allocation, the variation induced during assembly is not as intuitive to understand, and requires a mathematical model to quantify at the planning stage. A variation propagation model was therefore developed and is shown in Figure 5.

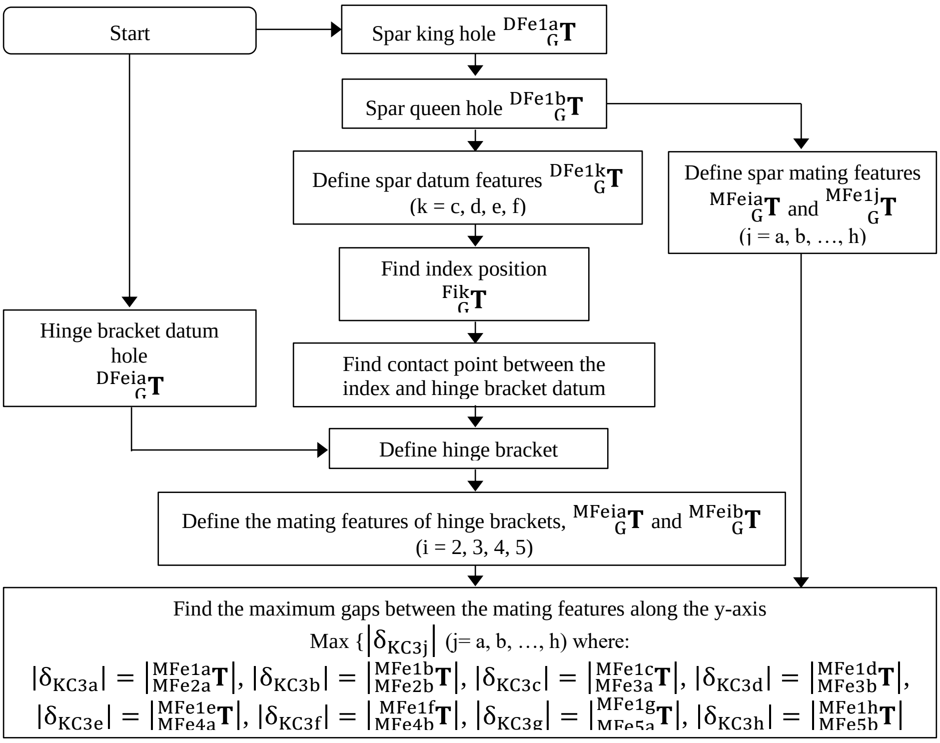

Figure 5. Variation propagation model flowchart.

4. Sensitivity Analysis and Results Discussion

The sensitivity study completed for this case study consists of the worst case variation being applied individually to each feature in the assembly, corresponding to the manufacturing operation used to create the feature. For example, to calculate the effect of the hinge bracket hole feature on the assembly variation level, the typical maximum and minimum variation of a drilling process is used, with all other features in the assembly were set to have zero variation. Each feature had the representative variation magnitude applied in both the X, Y and Z directions separately. The effect of manufacturing variation, plus any variation propagation at the assembly stage can then be calculated. The study was then repeated for the next feature, until all features that affect variation were tested. The key variation drivers are thus the features in the assembly that cause the largest variation of the assembly KCs from nominal. With no variation present, there is a perfect contact between the spar and each hinge bracket. Variation induced at any given feature is propagated through the assembly and leads to assembly variation at the KC features in the form of either a gap or a clash between the spar and hinge bracket. The sensitivity study allowed the effect of the manufacturing variation sources to be considered, to determine which creates the largest gap or clash at KC3. Table 2 shows the variation that was inputted into the variation model of the spar and hinge bracket assembly. From the sensitivity study, it can be seen that largest variation driver is variation due to the spar prepreg manufacturing process, which also had the largest magnitude of variation input.

Table 2. Sensitivity study inputs and results

Variation Source	Magnitude of part variation inputs (mm)	Magnitude of largest calculated gap or clash in assembly (mm)	Rank of variation effect
Variation A	+0.1250, -0.1250	0.1348	4
Variation B	+0.1900, -0.1900	0.2048	3
Variation C	+0.6000, -0.1900	0.6468	1
Variation D	+0.2000, -0.2000	0.2156	2
Variation E	+0.0100, -0.0100	0.0108	5
Variation F	+0.0100, -0.0100	0.0108	5

It can be seen that the variations experienced at the KC3 interfaces are larger than the manufacturing variation alone for each variation source, despite only one variation being tested at a time. The sensitivity analysis give the variation scale and the rank of the variation effects, so as to provide target directions to control the variation source.

5. Conclusion

Due to the ambiguous KC delivery chains of overconstrained assemblies, quantifying the final assembly variation presents an extra challenge compared to connective assemblies. This paper highlighted the importance of modelling variations induced by the assembly process, in addition to sub-component manufacturing variation, when dealing with overconstrained assemblies, in order to more accurately estimate the gaps and clashes that will occur at assembly. Variation sources were analysed and modelled for a representative industrial case study, consisting of an aircraft wing spar and hinge brackets. A variation propagation model was tested, and a sensitivity study carried out to identify the most significant variation drivers in the assembly.

Acknowledgements

The funding support from EPSRC project EP/P025447/1 is acknowledged. The funding support from EU H2020 RISE 2016 - ECSASDPE 734272 project is also acknowledged.

References

[1] B. Standard, Variation management of key characteristics, BSI Standards Publication, London, 2015.
[2] M. Morgan et al., Shimless Aerospace Assembly, in *SAE 2015 Aerotech, Seattle, United States*, 2015.
[3] J. Shi, *Stream of Variation Modeling and Analysis for Multistage Manufacturing Processes*, CRC Press, Boca Raton, 2006.
[4] Z. Kong *et al.*, Variation Propagation Analysis for Multistation Assembly Process With Consideration of GD&T Factors, *J. Manuf. Sci. Eng.*, (2009).
[5] T. Hussain, Modelling and Controlling Variation Propagation in Mechanical Assembly of High Speed Rotating Machines, 2012.
[6] Y. Ding *et al.*, Process-oriented tolerancing for multi-station assembly systems, *IE Trans.* (2005), 493-508.
[7] W. Huang *et al.*, Stream-of-Variation Modeling—Part I: A Generic Three-Dimensional Variation Model for Rigid-Body Assembly in Single Station Assembly Processes, *J. Manuf. Sci. Eng.*, (2007), 821.
[8] W. Huang *et al.*, Stream-of-Variation (SOVA) Modeling—Part II: A Generic 3D Variation Model for Rigid Body Assembly in Multistation Assembly Processes, *J. Manuf. Sci. Eng, (2007),* 832.
[9] K. W. Chase, Tolerance allocation methods for designers, *ADCATS Rep.* (1999).
[10] M. F. Ashby, *Material Selection in Mechanical Design*. Oxford: Butterworth-Heinemann, Oxford, 1999.
[11] V. McKenna *et al.*, Variation Model and Analysis of Spatial Assembly with Multiple Closed Chains, in *Advances in Manufacturing Technology XXXI* (2017), 555–560.